IMPLEMENTATION OF MULTIPLE FAN BEAM PROJECTION TECHNIQUE IN OPTICAL FIBRE PROCESS TOMOGRAPHY

LEONG LAI CHEN

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Specially dedicated to my beloved family,
who is the pillar of my strength…

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ABSTRACT

The application of optical sensors in process tomography involves using non-intrusive sensors to obtain vital information in order to produce images from the dynamic characteristics of a process system. The implementation of multiple fan beam projection technique is a novel approach in Optical Fibre Process Tomography using cost-effective optical fibre sensors with the aim to achieve a high data acquisition rate. For the thirty-two pairs of sensors used, the 2-projection and 4-projection techniques are being investigated. In comparison, the 4-projection technique yields better data acquisition rate, to more than 600 frames per second. In order to facilitate data acquisition process by controlling the operation of hardware interfacing in an efficient manner with less circuitry, low energy consumption and less heat dissipation, the PIC microcontroller and the sample and hold circuit are being used. Data obtained from optical fibre sensors will then be reconstructed into image using the Linear Back Projection and Iterative Reconstruction algorithms through Visual C++ programming. Concentration measurements from the reconstructed images are then used to obtain the mass flow rate of the solid/gas flow in a gravity flow rig. Series of error analyses show that the designed optical fibre sensors is feasible in performing as an instrument in solid flow visualization and as a mass flow rate meter, which is able to measure the mass flow rate at the range of not more than 40 percent of the plastic bead flow.

ABSTRAK

Aplikasi penderia optik dalam proses tomografi melibatkan penggunaan penderia yang tidak mengganggu aliran bahan dan berupaya memperoleh informasi-informasi penting daripada sifat dinamik sesuatu sistem untuk menghasilkan imej. Teknik sinaran berbilang alur kipas menggunakan penderia gentian optik dengan harga yang berpatutan adalah kaedah yang julung-julung kali diaplikasikan dalam Proses Tomografi Gentian Optik dengan tujuan meningkatkan kadar perolehan data. Untuk tiga puluh dua pasang penderia yang digunakan, teknik 2-unjuran dan 4-unjuran telah dikaji. Secara perbandingan, teknik 4-unjuran dapat mencapai kadar perolehan data yang lebih tinggi, iaitu lebih daripada 600 kerangka dalam satu saat. Untuk memudahkan proses pemindahan data daripada penderia kepada computer melalui pengawalan operasi perkakasan yang berkesanan dengan pengurangan jumlah litar, pengurangan penggunaan tenaga dan peresapan haba, pemproses mikro PIC dan litar sampel dan pegang telah digunakan. Data yang didapati daripada gentian penderia optik akan ditukarkan kepada bentuk imej menggunakan kaedah unjuran lelurus berbalik dan kaedah pembinaan berlelar melalui pogram Visual C++. Profil konsentrasi yang didapati daripada image kemudiannya digunakan untuk mendapatkan kadar aliran jisim untuk pepejal/gas di dalam peralatan aliran graviti. Analisis kesilapan yang dijalankan membuktikan kebolehpercayaan sensor gentian optik yang direka untuk berfungsi sebagai meter untuk melihat imej keratan rentas dan juga sebagai alat pengukur kadar aliran jisim yang berupaya mengukur kadar aliran jisim dalam julat tidak lebih daripada 40 peratus aliran pepejal plastik.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xi
	LIST OF FIGURES	xii
	LIST OF ABBREVIATIONS	xvi
	LIST OF APPENDICES	xix
1	**INTRODUCTION**	1
	1.1 Process Tomography Overview	1
	1.2 Background Problems	2
	1.3 Problem Statements	4
	1.4 Importance of Study	6
	1.5 Aims and Objectives of the Thesis	7
	1.6 Research Scopes	8
	1.7 Organization of the thesis	10
2	**TOMOGRAPHY SYSTEM OVERVIEW**	12
	2.1 Introduction	12
	2.2 Types of Tomography Sensors	13
	2.2.1 Positron Emission Tomography (PET)	14

		2.2.2 X-Ray Computed Tomography (CT)	15
		2.2.3 Magnetic Resonance Imaging (MRI)	16
		2.2.4 Electrical Capacitance Tomography (ECT)	17
		2.2.5 Electrical Charge Tomography	19
		2.2.6 Electrical Impedance Tomography (EIT)	20
		2.2.7 Ultrasonic Tomography	21
		2.2.8 Optical Tomography	22
	2.3	The Proposed System	23
		2.3.1 Type of Projection	23
		2.3.2 Optical Fibre Process Tomography (OFPT)	25
	2.4	Summary for Chapter 2	26
3	**FORWARD PROBLEM AND INVERSE PROBLEM**		27
	3.1	Introduction	27
	3.2	Forward Problem	28
		3.2.1 Projection Geometry	28
		3.2.2 Sensor Modelling	34
		3.2.3 Sensitivity Maps	42
	3.3	Inverse Problem	47
		3.3.1 Linear Back Projection Algorithm (LBP)	47
		3.3.2 Iterative Reconstruction Algorithn (IRA)	52
	3.4	Image Quality Assessment	55
	3.5	Mass Flow Rate (MFR)	58
	3.6	Summary for Chapter 3	60
4	**HARDWARE CONSTRUCTION**		61
	4.1	Introduction to the Hardware System	61
	4.2	Selection of Emitters and Receivers	62

	4.3	Preparation of Optical Fibres	66
	4.4	Fibre optic coupling	70
	4.5	Optical Fibre Sensor Fixture Design	71
	4.6	Circuit Design	72
		4.6.1 Infrared Projection Circuit	73
		4.6.2 Signal Conditioning Circuit	75
		4.6.3 Microcontroller signal controlling circuit	78
		4.6.4 Sample and Hold (S/H) Circuit	81
		4.6.5 Data Acquisition Terminal Circuit	83
	4.7	Summary for Chapter 4	85
5	**DATA ACQUISITION SYSTEM AND SOFTWARE DEVELOPMENT**		87
	5.1	Data Acquisition System (DAS)	87
		5.1.1 Differential/Single-Ended Selection	88
		5.1.2 Data Conversion Modes	89
		5.1.3 Digital Control Signal TGOUT	89
		5.1.4 Direct Memory Access (DMA)	90
	5.2	Software Development	90
		5.2.1 Graphic User Interface (GUI) Features	91
		5.2.1.1 Forward Modelling GUI	91
		5.2.1.2 Real-time Application GUI	94
		5.2.1.3 Image analysis GUI	101
		5.2.2 Programming Structures	103
		5.2.2.1 DAS Operation	103
		5.2.2.2 Image Reconstruction	105
		5.2.2.3 Draw Histogram	107
		5.2.2.4 Display Numerical Sensor Values	108
		5.2.2.5 Colour Properties	109
	5.3	Summary of Chapter 5	110

6	**RESULTS AND ANALYSIS**			111
	6.1	Introduction		111
	6.2	Measured Signals from Oscilloscope		111
		6.2.1	Photo-sensors	112
		6.2.2	Microcontroller Controlling Signals	113
		6.2.3	Output Voltages	116
	6.3	Data Acquisition Rate (DAR)		117
	6.4	Concentration Measurements from Sensor Modelling		119
		6.4.1	Static Distribution Flow Models	120
			6.4.1.1 Single Object Flow Models	120
			6.4.1.2 Multiple Objects Flow Models	129
		6.4.2	Overall Discussion	135
	6.5	Real-Time Concentration Measurements		136
		6.5.1	Static Flow Experiments	136
		6.5.2	Dynamic Flow Experiments	141
		6.5.3	Overall Discussion	147
	6.6	Mass Flow Rate Results		147
	6.7	Image Processing Rate (IPR)		152
	6.8	Summary of Chapter 6		154
7	**CONCLUSIONS AND FUTURE SUGGESTIONS**			155
	7.1	Conclusions		155
	7.2	Significant Contributions towards Process Tomography		155
	7.3	Recommendations for Future Work		156
REFERENCES				159
Appendices A – I				170 - 205

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Types of projections in tomography.	24
3.1	Mapping sensors to image plane by using Cartesian coordinates.	31
3.2	The full coordinates of all the sensors from P0 to P63.	33
4.1	Selection of infrared emitters.	64
4.2	Selection of photodiodes.	65
6.1	Light sequence for transmitters in one frame.	115
6.2	DAR for different projection modes.	118
6.3	Properties of single flow objects.	121
6.4	Assessment of reconstructed images for objects A, B and C.	127
6.5	Improvement of reconstructed image using SIE error analysis.	129
6.6	Assessment of reconstructed images for two and four objects flow model.	133
6.7	Improvement of reconstructed image using SIE error analysis.	135
6.8	Assessment of error analyses for reconstructed images.	140
6.9	Average mass flow rates obtained from flow rig calibration.	149
6.10	Percentage of flow obtained from concentration profiles.	150
6.11	Slopes and corrective coefficients for MFR graphs.	151
6.12	Investigation of image processing rate using different computer speeds.	153

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Principal components of a process tomography system.	12
2.2	Basic CT imaging system (Dove, 2001).	15
2.3	Schematic diagram of ECT system (Hui *et al.*, 1999).	18
3.1	Illustration of forward problem and inverse problem.	27
3.2	Optical fibre sensors arrangement on sensor's fixture.	29
3.3	Optical fibre sensors mapping platform.	30
3.4	Dividing the circle into four quadrants.	31
3.5	Single transmitter light emission.	35
3.6	Tangent modelling of sensors.	36
3.7	An example of an object intercepting a light beam.	40
3.8	Fan beam projection map	43
3.9	The actual flow image plane.	44
3.10	The basic idea of solving the inverse problem.	47
3.11	Implementing back projection algorithm in image space (Chan, 2002) a) Projection b) Back projection.	48
3.12	Overlapping of pixels using LBP for parallel beam.	49
3.13	LBP concept in fan beam projection a) Different back projected rays resulted from fan beam emanation b) Ray summation for fan beam projections.	50
3.14	Redefinition of pixel.	55
3.15	Flow rig calibration process.	59
4.1	Topology of the hardware construction.	61
4.2	Emitter characteristics (Electus Distribution, 2001) a) LED b) Laser diode	63
4.3	Electromagnetic spectrum of light.	64

4.4	Infrared emitter (left) and photodiode receiver (right).	66
4.5	Fibre optics configurations.	67
4.6	Optical fibre end termination a) Drawing b) Actual photograph	68
4.7	The acceptance angle for optical fibre.	68
4.8	Determining emission angle.	69
4.9	Coupling between sensor and fibre optic.	70
4.10	PVC housing a) 3-dimensional view b) Bottom view c) Coupling with infrared emitter.	70
4.11	Top view and side view of the sensor fixture.	71
4.12	Optical fibre sensor fixture a) 3-dimensional view b) Internal view	72
4.13	Infrared projection circuit.	73
4.14	Current-to-voltage converter circuit.	75
4.15	Non-inverting voltage amplifier circuit.	76
4.16	Pin diagram of PIC16F84A.	78
4.17	PIC16F84 circuit connection.	79
4.18	Binary counter and decoder circuit.	80
4.19	Bilateral and 2-way switch connections.	81
4.20	Sample and hold circuit.	82
4.21	Cabling and connections for attaching the STA-1800HC.	83
4.22	Connection of the signals from IDC cable to the 37-pin male connectors.	84
4.23	Actual photographs of the hardware system a) Sensor's area b) Signal control and conditioning board c) DAS terminal board	86
5.1	Connection of signal source to DAS.	88
5.2	Timing relationship between burst mode conversion and pacer clock.	89
5.3	TGOUT signal from DAS.	90
5.4	Mainframe of modelling GUI.	92
5.5	Flow chart of modelling GUI.	93
5.6	Mainframe of real-time GUI.	94
5.7	GUI operation settings a) Projection technique	

	b) Algorithm selection c) Operating mode	95
5.8	Selection on number of iteration	95
5.9	Control buttons for the software a) Initialization of DAS b) Start data acquisition process c) Stop data acquisition process d) Exit the program	96
5.10	Tomogram and colour bar.	96
5.11	Colour setting for the tomogram and colour bar.	96
5.12	Example of sensor's value window for Tx3.	98
5.13	Example of histogram window.	98
5.14	Flow chart for real-time GUI.	99
5.15	Offline simulation flow chart.	100
5.16	Image analysis GUI.	101
5.17	Flow chart of the image analysis GUI.	102
5.18	Flow chart to open and initialize DriverLINX.	103
5.19	Setting DAS properties in preparation for data acquisition tasks.	104
5.20	Flow chart to compute the LBP algorithm.	105
5.21	Flow chart to implement iterative reconstruction algorithm.	106
5.22	Flow chart of the histogram operation.	107
5.23	Flow chart of numerical sensor value display.	108
5.24	Flow chart of colour settings for the GUI.	109
6.1	Photo-receivers' transient response a) BPW85B b) SFH484-2	112
6.2	Microcontroller output signals in 2-projection mode (16 pulses)	113
6.3	Microcontroller output signals in 4-projection mode (8 pulses)	114
6.4	Timing and output control signals.	114
6.5	Output voltages for Rx23 in various stages a) Pre-amp and amplification output signals b) Amplified output signals, S/H_DI signal and output signals for S/H	116
6.6	Total conversion time for one frame data a) 2-projection b) 4-projection	118
6.7	Comparison of DAR and resolution.	119

6.8	Tomogram results for object A.	123
6.9	Tomogram results for object B.	125
6.10	Tomogram results for object C.	126
6.11	SIE, MSE and PSNR error analyses a) Object A b) Object B c) Object C	128
6.12	Tomogram results for two objects flow model.	131
6.13	Tomogram results for four objects flow model.	133
6.14	SIE, MSE and PSNR error analyses a) Two objects flow model b) Four objects flow model	134
6.15	Comparison of reconstructed tomograms.	139
6.16	SIE and PSNR error analyses for reconstructed images.	140
6.17	Miniature flow rig for dynamic flow experiment a) Valve at ‘close’ position / non-flow b) Valve at ‘open’ position.	141
6.18	Tomogram images for real-time plastic bead flow using filters.	146
6.19	Flow rig calibration curve for plastic beads.	149
6.20	Relationship between average MFR and iteration number.	150
6.21	Relationships between average MFR and percentage of flow.	151

LIST OF ABBREVIATIONS

θ	-	angle
Ω	-	ohm
±	-	more or less
°	-	degrees
1-D	-	1-dimension
2-D	-	2-dimension
3-D	-	3-dimension
A	-	Ampere
A/D	-	Analog to Digital Converter
API	-	Application Programming Interface
B/E	-	Base/Emitter transistor junction
C/E	-	Collector/Emitter transistor junction
CH	-	Channel
CPU	-	Computer Processing Unit
CT	-	Computed Tomography
DAR	-	Data Acquisition Rate
DAS	-	Data Acquisition System
DDB	-	Device Dependent Bitmap
DIB	-	Device Independent Bitmap
DSP	-	Digital Signal Processor
DLL	-	Dynamic Link Library
ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
EMI	-	Electromagnetic Interference
fps	-	frame per second
g/m^3	-	gram per metre cube

g/s	-	gram per second
GaAIA	-	Gallium Aluminium Arsenide
GHz	-	Giga Hertz
GND	-	Ground
GUI	-	Graphic User Interface
Hz	-	Hertz
I/O	-	Input/output
IBM	-	International Business Machine
IDC	-	Insulation Displacement Connectors
IR	-	Infrared
IRA	-	Iterative Reconstruction Algorithm
ISA	-	Industry Standard Architecture
IV	-	intravaneous
keV	-	kiloelectron volt
kg/s	-	kilogram per second
kHz	-	kiloHertz
kS/s	-	kilo Samples per second
kΩ	-	kilo Ohm
LBP	-	Linear Back Projection
LCD	-	Liquid Crystal Display
LED	-	Light Emitting Diode
mA	-	miliAmpere
MFC	-	Microsoft Foundation Classes
MHz	-	MegaHertz
mm	-	milimetre
MRI	-	Magnetic Resonance Imaging
ms	-	milisecond
MSB	-	Most Significant Bit
MSE	-	Mean Squared Error
mV	-	miliVolt
mW	-	miliWatt
N	-	No
N/A	-	non-available
nF	-	nanoFarad

nm	-	nanometre
ns	-	nanosecond
O/P	-	output
OFPT	-	Optical Fibre Process Tomography
OFS	-	Optical Fibre Sensor
OOP	-	Object Oriented Programming
PC	-	Personal Computer
PCB	-	Printed Circuit Board
PCI	-	Peripheral Component Interconnect
PDA	-	Personal Digital Assistant
PET	-	Positron Emission Tomography
pF	-	pikoFarad
pix	-	pixel
pix^2	-	pixel square
PSNR	-	Peak Signal to Noise Ratio
PVC	-	Polyvinyl chloride
QI	-	Quadrant 1
QII	-	Quadrant 2
QIII	-	Quadrant 3
QIV	-	Quadrant 4
RM	-	Ringgit Malaysia
Rx	-	Receiver
S/H	-	Signal Sample and Hold
SIE	-	Spatial Image Error
TV	-	Television
Tx	-	Transmitter
™	-	Trade Mark
USD	-	United States Dollar
XTAL	-	Crystal
Y	-	Yes

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Projection geometries for sensors	170
B	Normalized sensitivity maps for Tx0 using rectangle-based normalization.	174
C	Normalized sensitivity maps for Tx0 using projection-based normalization.	180
D	Assembly language source codes for PIC16F84A.	186
E	Program listing for *InitDAS()* subroutine.	190
F	Program listing for subroutines *GetFromDAS()* and *clearBuffers()*.	191
G	Program listing of subroutines to perform the LBP and IRA.	194
H	Predicted and measured normalized sensor loss of the selected flow models.	201
I	Published paper/journal and accepted abstracts.	205

CHAPTER 1

INTRODUCTION

1.1 Process Tomography Overview

The widespread need for direct analysis of the internal characteristics of process plants in order to improve the design and operation of equipment has made process tomography a main research activity within the industrial instrumentation. Originated from the Greek words *'tomos'* which means slice and *'graph'* meaning picture, tomography can be defined as a slice of a picture (Williams and Beck,1995). In simple terms, tomography is an imaging technique that enables one to determine the contents of a closed system without physically looking inside it.

The concept of tomography was first published as early as 1826, by Abel, a Norwegian physicist, for an object with axi-symmetrical geometry. In 1917, an Austrian mathematician, Radon, extended Abel's idea for objects with arbitrary shapes. During the 1970's, tomography is used in diagnostic medicine by utilizing x-rays to form images of tissues based on their x-ray attenuation coefficient. Godfrey Hounsfield and Allen Cormack were jointly awarded the Nobel Prize in 1979 for their pioneering work on X-ray Tomography.

Process Tomography was originally developed for medical scanners, thus tomography is often perceived as an imaging tool for medical examination purposes. The industrial process tomography (IPT) began in the 1930s when much attention was paid to resistivity sounding. This technique involved passing currents through the ground to determine the location of mineral deposits and geological structures, and geophysical exploration remains an important application of tomography today. But it was not until about 50 years later that people began to investigate low-cost methods to image the flows in pipes and vessels found in manufacturing. This work was pioneered by researchers at the University of Manchester Institute of Science and Technology (UMIST) in the UK and the Morgantown Energy Technology Center in the US. Process Tomography has since been grown globally to other countries such as Norway, Netherlands, Finland, Sweden, Germany, China, Japan, Malaysia and many others.

There are different requirements in an industrial environment than there are within a medical one: different regulations regarding for example use of ionising modalities and different speed requirements (West *et al*., 1999). Technically, Process Tomography can be described as imaging process parameters in space and time. Important flow information such as concentration measurement, velocity, flow rate, flow compositions and others can be obtained without the need to invade the process or object. As a result, cross sectional images of processes generate better online inspection, monitoring and process control - promoting improved yields and more effective utilization of available process capacity. Potentially, tomographic systems may also be an alternative approach in developing and verifying process theories and models, as well as for improving process instrumentation (Dechsiri *et al*., 2003).

1.2 Background Problems

The earlier researches done by Ruzairi (1996), Sallehuddin (2000), Khoo (2002) and Hisyamuddin (2002) have shown that the optical fibre sensor is applicable in flow visualization (image reconstruction). The acquired concentration profile from the image reconstruction is needed together with the velocity profile to complete the mass flow rate estimation in a pneumatic conveying system. Basically, the principle of measurements in tomography is to obtain all possible combinations of measurements from the sensor system. The higher the measurements obtained from the sensors, the resolution of the system would be better.

By using the parallel projection, previous researches have each faced the problem of obtaining a high resolution of their system. This is because the parallel projection method limits the number of measurements to the number of sensors being used. In his research, Chan (2002) has implemented the switch-mode fan beam projection technique to obtain flow visualization using LED as light source but resolution and the number of sensors in his system is limited by the physical size of the LED emitters. Thus, this research will focus in implementing the switch-mode fan beam method using optical fibre sensors to increase both the number of sensors and number of measurements in order to obtain a system with high resolution.

Heat dissipation (measured by the unit Watt) in electrical and electronic devices is a problem often faced by many researchers. Previous researchers in optical fibre process tomography (OFPT) used the halogen lamp as light source. Inside the halogen lamp, contains the halogen gas. At the centre of the lamp is a tungsten filament. For the halogen lamp to function, electricity heats up this filament and the halogen gas will combine with tungsten vapour. The halogen may not adequately vaporize or fail to adequately react with the tungsten if the bulb is too cool. Thus, the halogen bulb surface must be very hot, generally over 250 degrees Celcius (482 degrees Fahrenheit) (Khoo, 2002).

This high temperature of the halogen bulb surface will cause massive heat dissipation to the fibre optics and if proper cooling systems, such as fans are not installed near the halogen lamp to circulate heat, the fibre optics might melt. To solve this problem, it is better to take precaution by choosing a transmitting device which does not produce heat dissipation as much as the halogen lamp; and the infrared is being selected as light source in this research. The laser diode is not chosen due to its high costs and LED is not preferred because the LED light is considered as visible light which can easily influenced by noise from the surrounding environment light source.

In the optical tomography field, many researches have concentrated on the back-projection algorithms originally developed for x-ray tomography. The Linear Back Projection (LBP) method is the simplest in concept and the easiest to understand, but it produces reconstruction with substantial artefacts (Oyvind, 1996). Sallehuddin (2000) and Chan (2002) have introduced back projection filtering techniques which managed to achieve better image quality. Alternatively, the use of *priori* knowledge would improve image quality (Dyakoswki, 1996). The iterative reconstruction method used in ECT provides a way of incorporating a *priori* information into the image reconstruction and this technique will be investigated in this research.

1.3 Problem Statements

The design and development of an optical fibre process tomography (OFPT) (Chunsheng *et al.*, 2002) requires understanding and knowledge in various fields. The mechanical field covers the sensor fixture or flow rig design. The electrical and electronic fields include the power dissipations, electronic devices and digital systems whereas the instrumentation and control fields comprise of sensor design and data acquisition process. In addition, the study on medical field is important to apply the image reconstruction techniques while the computer science field yields familiarity in designing application software using certain programming languages. Generally, the problems encountered and solutions obtained during this research are shown as below:

- The fibre optics coupling with transmitters and receivers often results in signal loss. When signal loss occurs, the transmitters and receivers are not able to provide accurate physical signals to be processed. To solve this problem, a custom-made housing has been designed for the fibre optics and sensors coupling.

- The heat from the candle used to model the fibre optic lens does not give a standard and fixed shape of len's surface. Ramli (1998) and Sallehuddin (2000) have designed the lensing jigs but due to the unavailability of these jigs, time and cost constraints, the modelling are being done using the simple methods applied by Ruzairi (1996). The modelling of these fibre optic lenses will determine the projection angle of the light emitter, so experimental methods are used to obtain the desired angle.

- In real-time data acquisition, the data acquisition rate plays a major role in determining how 'real' the online measurement is. For a total number of 16 pairs of optical sensors employed by Chan (2002), the data acquisition rate obtained is 300 fps. In this research, the number of sensors is doubled to 32 pairs, thus the data acquisition rate will be theoretically lower. However, if the sampling rate or experimental span is too low, information about the detailed fluctuations of the continuous waveform signal will be lost (Makkawi and Wright, 2002). Therefore, the multiple projection technique is implemented in this research to attain a higher data acquisition rate for an increased number of sensors.

- To convert the analogue signals from the signal conditioning circuit, the Keithley DAS-1802HC high speed data acquisition board has been selected. The challenging task here is to study and perform the background operation using Direct Memory Access (DMA) technique together with the burst mode sampling in order to synchronize the data acquisition process with the microcontroller, signal conditioning circuit and also the sample and hold circuit.

- Compared to Visual Basic, the Microsoft Visual C++ version 6.0 programming language provides an added advantage of achieving a higher performance measurement in supporting the bulk processing codes for image reconstruction calculation because it is a fully compiled computer language in native language. Although the Visual C++ is able to accelerate the image processing rate of the tomogram, the image processing rate is still dependent on computer's processor speed. Since the DAS card available in this research can only be used in the computer with ISA slot, the image processing rate is limited by the Intel Pentium III 933 MHz processor.

1.4 Importance of Study

The implementation of fan beam projection in optical tomography is still in the early stages compared to the parallel projection method. The research carried out by Chan (2002) shows that the fan beam method results in a better resolution and precision of flow visualization in comparison to the parallel beam. This is because the switch-mode fan beam projection has the ability to obtain more measurements from a limited number of sensors.

The application of multiple switch-mode fan beam projection technique is a novel approach in optical fibre process tomography (OFPT). Sallehuddin (2000) has initiated the usage of fan beam projection method in optical fibre sensors but his research only yields a fixed transmission mode using the source directly from halogen light. In the research done by Chunsheng *et al*. (2002), diverging rays from a LED array are transformed into parallel rays by optical fibre coupling and collimating systems in the light emitting part.

By definition, multiple fan beam projection technique here is described as allowing more than one emitter to project light at the same time using the switch-mode fan beam method. There are two types of multiple projection technique involved which are the 2-projection and 4-projection techniques. When two or four transmitters project light at the same time, the total time to complete one frame of data acquisition will be shorter, thus it is believed that both these techniques are able to achieve better timing performances in data acquisition process when compared with the conventional single light projection used by Chan (2002).

Generally, with the implementation of multiple switch-mode fan beam projection technique together with fibre optics, it is believed that the resolution and hardware data acquisition rate of the optical system can be improved. Therefore, this will minimize data lost and is able to produce a more accurate real-time tomographic image. Further investigations on the mass flow rates of certain solid materials will determine the suitability of using the developed optical fibre sensor system in the process industry flows.

The importance of accurate, reliable and robust sensing technology for a wide range of industrial processes (Mark, 2004) is recognised by many industries. To be reliable, the sensor must be kept at a certain level of efficiency when operating in the plant. With this specific sensor requirement in mind, the operation of optical fibre sensors system in this research is being controlled by the computer and microcontroller. Since light goes through fibre optics and then diverged into fan beam before being received by the fibre optics at the receivers' boundary area, the system has to have high pulsed current to drive the transmitters.

When the power is supplied to the transmitters continuously for a long time, it will produce considerably high heat dissipations which will make it become hot. According to the forward current (IF) versus temperature graph (T) from the SFH 484 datasheet, it is shown that when power dissipation increases, the temperature increases and thus, the current of the emitter will decrease. For a LED or infrared, the relative efficiency is defined by the luminous intensity per unit current (Boylestad and Nashelsky, 1999).

This means that when temperature or heat dissipation increases, current will drop and so will the luminous intensity. To maintain the efficiency of the infrared in this research, the light projecting circuit will remain 'off' unless the computer sends a signal to the DAS and microcontroller to start light projection and data acquisition process. After the user stops the data acquisition process through software control, the light projecting circuit will once again become idle. In this way, the hardware system has low energy consumption and power resources can be conserved.

1.5 Aims and Objectives of the Thesis

The main aim of this research is to implement the multiple fan beam projection technique in optical fibre process tomography for flow visualization and determining the mass flow rate of the plastic bead flow in a gravity flow rig. The proposed technique opens the gateway to a new sensing method which is able to solve some of the problems faced by researchers in a cost effective way. The specific objectives of the research are shown as below:

1) Fully utilize fibre optics as the light transmitting and receiving mediums for the most suitable photo emitter-detector pair in the hardware construction.
2) Fabricate a 32-sensors prototype hardware system which implements the microcontroller based timing circuit. The completed sensor's system will be fixed to the gravity flow rig to obtain flow visualization and mass flow rate results.
3) Investigate the methods of implementing the multiple fan beam projection technique using switch-mode fan beam method to obtain at least a 600 fps data acquisition rate.
4) Solve the forward and inverse problems of the optical system by developing mathematical models, sensitivity maps and investigating the feasibility of applying iterative image reconstruction method used mainly in the 'soft-field' sensors into the optical fibre sensor system.
5) Develop a real-time image reconstruction software using Visual C++ 6.0 for a faster image processing rate.
6) Investigate the performance and capability of the developed system, including resolution, speed and also accuracy in flow concentration and mass flow rate.

1.6 Research Scopes

The research scopes are divided into:

i. Sensor’s fixture and selection of sensors

The first part of this scope is the mechanical design of sensor’s fixture, including the size of the suitable pipe, geometry of the sensor’s placement and preparation of the fibre optics. Next is investigating and comparing the performances of phototransistors and photodiodes in high frequency responses. Other characteristics to take into consideration in the optical sensor’s selection are the compatible emitter and receiver’s spectral responses, sensitivity, fast transient time and fast settling time.

ii. Circuit design

The circuit design is comprised of light projection circuit, signal conditioning circuit and also sample and hold circuit. The light projection circuit includes studies on selection of transistor that is able to support high (pulsed) current without overheating the circuit whereas signal conditioning circuit involves studies on current to voltage converters, signal amplifying circuit and wide bandwidth op-amps to support high frequency responses. Meanwhile, the sample and hold circuit needs understanding in sampling analogue signals. All completed circuits are fabricated onto the printed circuit board (PCB).

iii. Timing control and Data Acquisition System design

Timing control is the ‘heartbeat’ to the whole optical tomography system. In this research, it involves studies into using microcontroller to generate and control signals for the timing circuit. Other studies include investigating the achievable projection frequency and other associated signals to be used in communicating with DAS 1802HC as the gateway to interface with the computer.

iv. Software design to perform real time image reconstruction

This part of the research scope covers the learning of Visual C++ programming language, designing the graphic user interface (GUI), bitmap drawing and program optimization to achieve a fast image processing rate. In the DAS-1802HC acquisition system, function call driver involves the concept of direct memory access, burst clock, input trigger signal and output trigger signal.

v. Mass flow rate measurement
The mass flow rate measurement of solid material flows in gravity drop conveyor using a single layer sensor cannot be obtained directly through velocity measurement. Therefore, the flow rig calibration process for the selected solid flow need to be done to obtain the relation between the concentration and mass flow rate measurement.

1.7 Organization of the thesis

Chapter 1 discusses the process tomography overview, background problems, problem statements, importance of study, research objectives, and research scopes.

Chapter 2 presents the literature review of the research which relates to tomography system overview, types of tomography sensors and types of projection available in this field. The applications of tomography in industrial processes will also be explored.

Chapter 3 reviews the solutions to the forward and inverse problems. This chapter revolves in generating sensitivity maps to assist in image reconstruction process and developing forward models to simulate measurements for certain sensor projection geometry presented in this research. Meanwhile, the inverse problem here will describe the image reconstruction algorithms which are used in real-time flow visualization.

Chapter 4 is about the overall hardware development of the optical fibre sensors system. Selection of the most suitable photo emitter-detector pair is made and next is preparing the fibre optics to perform as transmitting and receiving mediums. A sensor fixture is designed to align the optical fibre sensors to the pipe. In order for the optical system to function, the circuit designs are discussed.

Chapter 5 gives an overview of the data acquisition system and also the software development. Firstly, the data acquisition operation using Keithley 1802HC is introduced. Then, the programming structure is presented whereby works are mainly discussed in the flow charts.

Chapter 6 discusses about all the results obtained in this research. The results analysis range from displaying the measured signals from oscilloscope during hardware preliminary testing, analyzing the achievable data acquisition rates, forward modelling results and also the real-time concentration measurement and mass flow rate results. In addition, an analysis of the image processing speed will be commenced.

Chapter 7 states the overall conclusions and the significant contributions of this research toward Process Tomography field. Suggestions for future work will be recommended as well.

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